

# SANDIA IN THE ARCTIC



THE ARCTIC  
SCIENCE AND  
SECURITY  
INITIATIVE  
REPORT  
2016-2019

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# ARCTIC TEAM



*"Sandia's work in the Arctic has long been an important component of our role as a federally funded research and development center, advising the Department of Energy's Office of Science on the interconnections between energy production, the environment, and national security, and on innovative ways to detect, repel, defeat, and mitigate threats. Our current efforts in the Arctic leverage Sandia's deep experience in computing, from verification and uncertainty quantification to multiphysics applications to increasingly complex numerical models, as well as our decades of experience in unique and quantitative Earth Sciences research. As we bring new high-performance computing and exascale platforms online, Sandia is in an even better position to provide predictive models of the complex and rapidly changing Arctic and the ramifications for the nation's energy and infrastructure security."*

*—Susan Seestrom  
Deputy Laboratories Director*

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## OPENING REMARKS

The Arctic is vast, with significant resources and commercial opportunities that many nations are interested in developing. The Arctic plays a significant role in the Earth's climate and weather systems, from the melting of Greenland's ice sheet to changes in the Polar Vortex. U.S. national security agencies are updating their strategies and capabilities to address emerging issues related to these changes.

*"Sandia's historic work laid a foundation of science and engineering that produced combustion and atmospheric science expertise for the Department of Energy's (DOE) transportation energy programs and global earth system model development for DOE's Energy Exascale Earth System Model."*

More than 50 years ago, Sandia developed skill in atmospheric chemistry and testing as a part of the Labs' nuclear deterrence mission. This historic work laid a foundation of science and engineering that produced combustion and atmospheric science expertise for the Department of Energy's (DOE) transportation energy programs and global earth system model development for DOE's Energy Exascale Earth System Model.

Sandia has had a presence in the Arctic for more than two decades, operating atmospheric radiation measurement facilities on Alaska's North Slope for the DOE Office of Science. Our scientists and engineers are addressing energy resilience for Arctic communities and our national defense, foundational research on the Arctic seafloor, coastal erosion, and atmospheric dynamics. We are developing new technologies for domain awareness and national security across the immense expanse of the Arctic and Antarctic.

This report describes a number of Sandia contributions to Arctic studies with suggestions for future research.



Steve Younger  
Director, Sandia National Laboratories

# A CHANGING ARCTIC

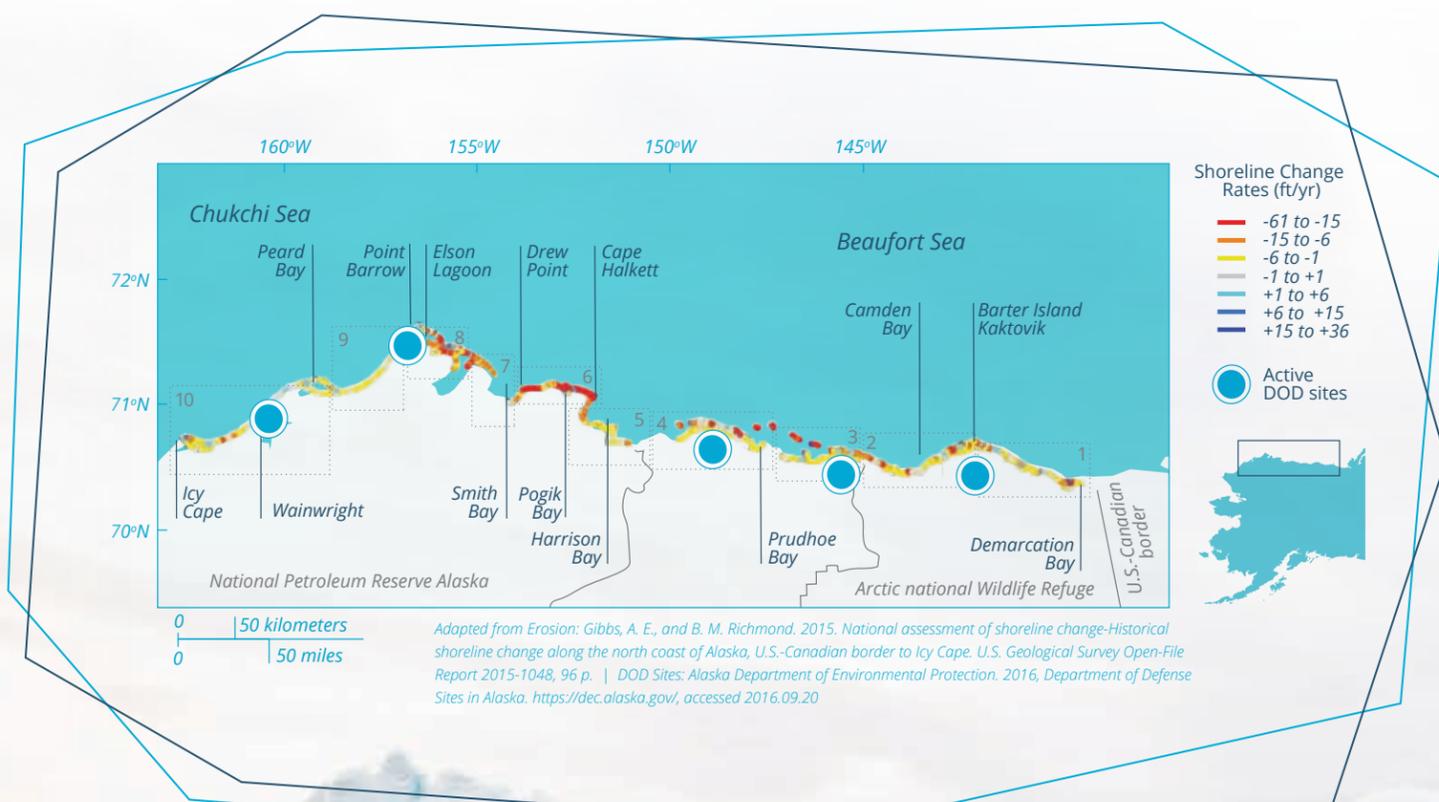
The Arctic region is experiencing an alarming amount of change, which is a strategic and human challenge. Changes are impacting the Arctic more rapidly than any other region on Earth, with average temperatures rising two to three times faster than the global average. Changing conditions are affecting the indigenous populations of northern Alaska who have survived hundreds of years largely through subsistence hunting, herding, and fishing. Native people have traditionally survived on seals, whales, walrus, and fish from the sea, or caribou, musk oxen, and other mammals from the land. Ocean ice that was previously frozen year-round is now too thin for dog sleds, which disrupts seasonal patterns of subsistence hunting. Once fertile fisheries are being destroyed at an alarming rate. Alaskan communities are struggling to hold onto their traditional way of life.



Thawing permafrost is threatening the foundations of buildings and homes, energy infrastructure, and roads and airstrips. Rising sea levels are eroding the coastline where most of the population lives, and entire villages are being relocated at significant expense to state and federal governments. High energy costs and unreliable energy supplies plague native communities, while extended periods without heat and power during frigid winter months pose risks to all inhabitants.

Changing conditions threaten not only Arctic communities, but also U.S. defense installations, and thus national security. The eroding coastline is encroaching on the Air Force North Warning System long-range radar facilities. Arctic change has led to increasing encroachments into U.S. airspace and waters by foreign militaries. Melting sea ice is opening previously closed channels, and these now need to be defended. As other countries increase their presence in the Arctic, the need for U.S. security missions will likely increase, creating greater demands for operational capacity. Together with increased commercial maritime activity, these will drive the need for more robust infrastructure and expanded emergency response capabilities.

The Arctic holds a disproportionate amount of the world's oil and gas reserves, as well as mineral resources. Melting sea ice has already led to the opening of the Northwest and Northeast passages in the summer, and receding glaciers have exposed new lands to mining operations. Many offshore oil and gas projects are proposed or already underway. These changes will create territorial disputes and increase international tensions, leading to an increased militarization of the Arctic. There is already a rapidly expanding non-U.S. presence in the region, which could heighten geopolitical sensitivities and create many operational and environmental hazards.



Both Arctic and non-Arctic nations are rapidly establishing a presence— Russia, China, Singapore, India, Japan, Korea, Saudi Arabia, United Arab Emirates, and others, are investing heavily in the region. The Arctic is strategically important to national security, but paradoxically the U.S. has the smallest presence among the Arctic Nations; even smaller than some non-Arctic Nations.

The U.S. has critical strategy and security gaps in the Arctic including a lack of adequate communications coverage, a robust power grid, and reliable sensing infrastructure. Costs to develop infrastructure are very high in Alaska. A better understanding of the system requirements in these harsh and rapidly changing conditions is critical. Finding solutions to these problems is exacerbated by the scarcity of scientific data and measurements and a general lack of understanding of many of the natural processes at work in the region.

The Arctic is a complex, highly coupled natural system with strongly interdependent components. As the sea ice melts, exposing vast expanses of open water, the high albedo (highly reflective) ice surfaces are replaced with darker, heat-absorbing ocean surfaces that cause temperatures to rise faster. Existing climate models often fail to accurately describe the unique conditions in the Arctic because these models were developed for regions of the earth with vastly different physical, chemical, and biological conditions. Current models used to predict coastal erosion, for example, do not accurately represent the unique way in which the Arctic coastline erodes, and thus, they underestimate the rate of coastal erosion.

# ISSUES IN A CHANGING ARCTIC

Melting ice increases maritime activity, natural resource development, tourism, and other activities

Critical need for Arctic-capable infrastructure and technologies

Newly opened coastlines require protection

Increasing encroachments in U.S. airspace and waters

Impact to infrastructure from thawing permafrost, coastal erosion, and flooding

World-wide implications such as rising global sea levels, changes in weather patterns, etc

More data and information needed to support planning in the Arctic

# SANDIA'S LONG HISTORY IN THE ARCTIC

Part of Sandia's responsibilities as a national laboratory serving the country is to anticipate, transform, and support solutions to address national security issues. Foundational to Sandia's Arctic program is the ability to leverage over two decades of research, development, and year-round operations in the region, often in collaboration with Arctic research institutions. These efforts include developing reliable, renewable energy systems; improving domain awareness with new sensor technologies, unmanned systems, and satellites; and analyzing interdependencies among environmental changes, economic development, increased human activity, risk, and security capabilities.



The Department of Energy (DOE) Office of Science funds Sandia to conduct research and operate two Arctic facilities in Alaska for the DOE Atmospheric Radiation Measurement (ARM) program. One is the ARM Climate Research Facility (ACRF) at Utqiagvik (formerly Utqiagvik/Barrow), and the other is the ARM Mobile Facility #3 (AMF-3) at Oliktok Point near Prudhoe Bay. The ACRF and AMF-3 have very similar capabilities to make detailed measurements of atmospheric behavior.

Collecting data in harsh and highly dynamic conditions in the High Arctic is necessary for research, forecasting, and regional and national planning. The ARM facilities support field experiments that help space satellite programs validate their systems and provide data for Earth system models. The ACRF has supported over 150 field campaigns since 1997 and maintains the longest continuous record of atmospheric data for the U.S. Arctic. The AMF-3 site at Oliktok Point is a possible location for a future High Arctic research facility.

Sandia participated in the SHEBA project in 1997, has operated DOE facilities in the Alaska Arctic since 1998, and managed controlled airspaces for DOE out of Oliktok Point for Arctic research



Using tethered balloons and drones, Sandia collects data related to atmospheric thermodynamics, cloud microphysics, and aerosol properties critical for weather forecasts, monitoring severe weather, and improving atmospheric models. Sandia also works with radar (such as synthetic aperture radar) and lidar (such as Raman lidar) systems, including hardware, software, algorithms, and data analysis, for the remote sensing of sea and land ice. Sandia recently completed the first continuous, long-term monitoring field campaign involving measurements of methane, black carbon, and other greenhouse gases at Utqiagvik, Alaska.

Sandia has applied its capabilities for numerous needs in high latitude regions: investigating renewable energy systems integration and advanced electrical grid technologies for Kodiak, Cordova, and Venetie, Alaska; managing nuclear materials for the U.S. Air Force; conducting remote sensing of permafrost; model development for the melting Greenland ice sheet; and using airborne synthetic aperture radar to detect subsurface changes in land and sea ice.



Examples of unmanned aerial systems deployed from the Sandia-managed facility at Oliktok Point (left-to-right): Aerostat tethered balloon, the BAT-3 (with New Mexico State University, 2012), and the Sierra (with NASA, 2013)



Atmospheric test chamber



Leading-edge Raman Spectroscopy laser diagnostics developed for studying gas transfer systems critical to the Nuclear Weapons program



Sandia research team with DOE and NOAA on Arctic sea ice for one year with the Surface Heat Budget of the Arctic Ocean (SHEBA) Project



Sandia actively manages ARM program Arctic site; latest generation Raman LIDAR deployed in 2010

1950

1960

1970

1980

1990

2000

2011

Cloud research & monitoring innovations to plan high altitude and ballistic tests



Atmospheric research (Salton Sea and Tonopah) to permit Above Ground testing

As a result of the Energy Crisis, the Combustion Research Facility (CRF) was established to focus on laser diagnostic and computing capabilities for analyzing gas mixing.



Sandia recognizes opportunity to apply CRF diagnostic capabilities to remote atmospheric monitoring and assists in planning ARM program



Establishes Arctic site in Alaska (at former Defense Early Warning site)

Sandia competes successfully for ARM program support, develops and deploys Raman LIDAR for tropospheric water vapor studies and first ARM cloud stations



Sandia and LANL partner to operate an advanced mobile atmospheric monitoring lab. This work led to advances for other national security domains, e.g. CALIOPE for non-proliferation

The Sandia Atmospheric Sciences group has supported observations and field campaigns for the DOE ARM Program since 1997.

# SANDIA'S RECENT ARCTIC INVESTMENTS

In 2015, Sandia executive management decided to leverage this history to formally establish an Arctic science and security initiative. Seed funding was provided, as part of the Laboratories' Mission Area Alignment Initiative, to provide opportunities for integrated, cross-laboratories research in Arctic security, energy, infrastructure, and science to address:

- » Identifying emerging national security challenges, near- and long-term;
- » Strengthening the nation's technological superiority through R&D;
- » Developing products and services essential for national security challenges; and
- » Informing technology policy, critical to preserving security and freedom throughout the world, consistent with Sandia's mission as a national security lab.

A laboratories-wide brain-storming session, referred to as the Arctic Innovation Tournament, was held in late 2015. The effort produced eight white papers and three roadmaps on Arctic security, science, and infrastructure. In 2016, Arctic-related ideas were solicited in calls for laboratory-directed research and development (LDRD, internally funded) proposals, and 17 Arctic LDRD ideas were submitted that year. Over the last three years, nearly \$10M in Arctic-related LDRDs have been funded including:

- » Attribution of methane emissions in the Arctic and continental U.S.
- » Deciphering atmospheric ice nucleation using molecular-scale microscopy
- » High-resolution measurements and modeling of Arctic clouds
- » Predictive modeling of Arctic coastal erosion
- » Addressing Arctic tipping points that can trigger global change
- » Forecasting ocean wave energy
- » Evaluating the capability of high-altitude infrasound platforms to cover gaps in existing networks (Heliotrope project)
- » Developing fugitive emissions sensor networks: new optimization algorithms for monitoring, measurement and verification
- » Forecasting marine sediment properties using geospatial machine learning
- » Demonstrating bifacial solar photovoltaics in Fairbanks, AK



<p>FISCAL YEAR <b>2016</b> OCT-SEPT</p>	<ul style="list-style-type: none"> <li>» Conduct discovery to identify internal capabilities</li> <li>» Discuss opportunities with Sandia Leadership and technical staff</li> <li>» Identify opportunities</li> <li>» Innovation Tournament</li> <li>» Build capability and investment pipeline</li> </ul>
<p>FISCAL YEAR <b>2017</b> OCT-SEPT</p>	<ul style="list-style-type: none"> <li>» Arctic topics submitted for LDRDs</li> <li>» Develop external partnerships and visibility</li> <li>» Inform partners and stakeholders</li> <li>» Prep for National Lab Day at UAF in Fairbanks, Alaska</li> </ul>
<p>FISCAL YEAR <b>2018</b> OCT-SEPT</p>	<ul style="list-style-type: none"> <li>» Participate in National Lab Day at UAF</li> <li>» Seek funding opportunities to enhance external visibility</li> <li>» Strengthen critical partnerships through collaborative engagements and projects</li> </ul>
<p>FISCAL YEAR <b>2019</b> OCT-SEPT</p>	<ul style="list-style-type: none"> <li>» Support Sandia Departments with Arctic capabilities and interests</li> <li>» Active engagement across Sandia Mission areas</li> <li>» Enhance broad communication of Arctic opportunities</li> <li>» Develop Arctic strategies for individual Divisions</li> <li>» Encourage staff collaboration</li> </ul>

Concurrently, two Sandia Departments (Atmospheric Sciences/8863 and Robotics/8634) jointly executed a capability to fly Sandia unmanned aircraft systems (UAS) at Oliktok Point as part of a strategic investment in a High Arctic research center concept. Organizations involved in developing the U.S. High Arctic Research Center (USHARC) concept include multiple Centers at the University of Alaska at Fairbanks (UAF) and the Woodrow Wilson Center Polar Institute.

In addition to cultivating new partnerships, Sandia solidified agreements with existing partners such as UAF via Cooperative Research and Development Agreements (CRADAs).

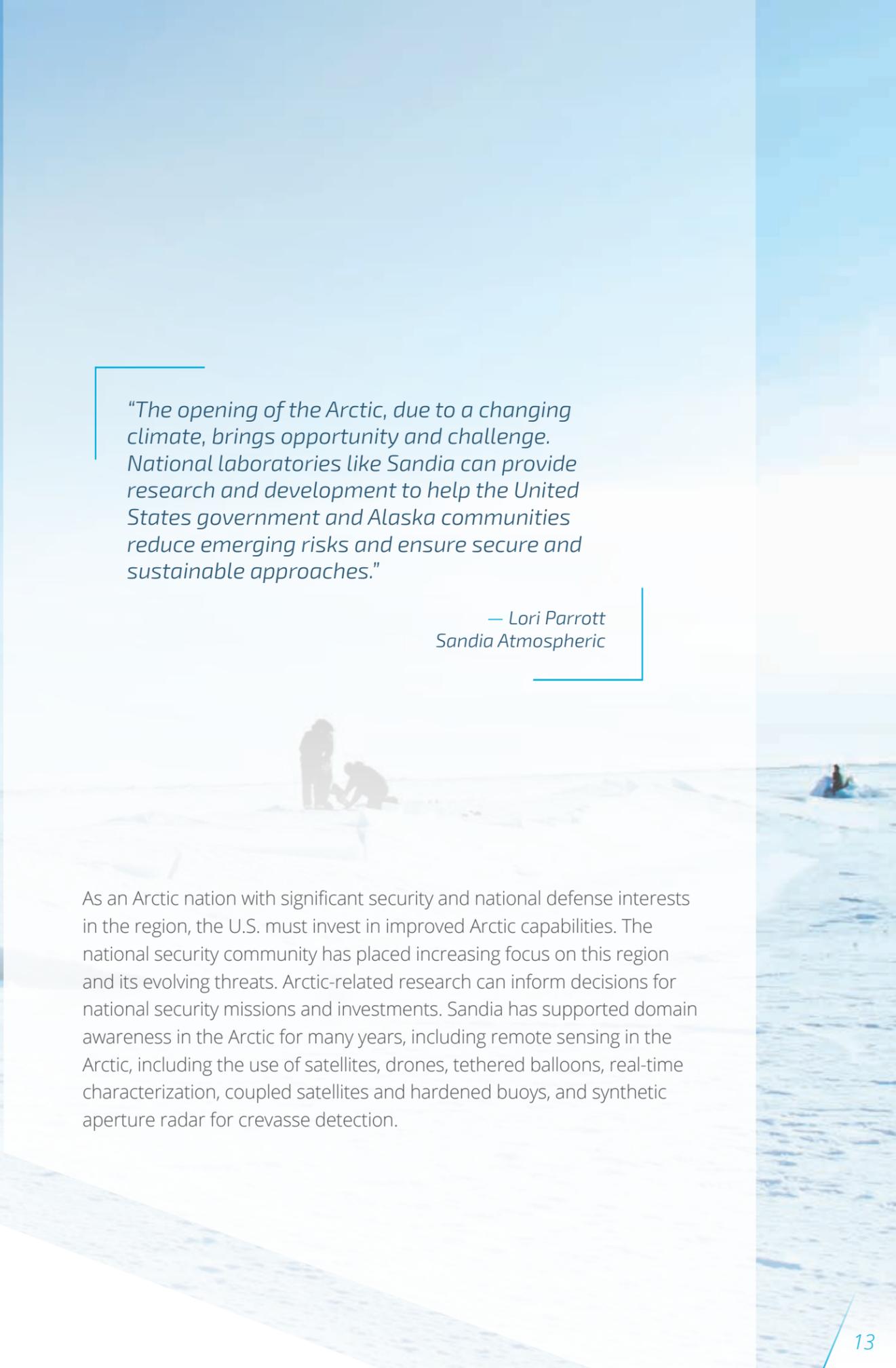
Alaska National Lab Day was an event held the end of May 2018 on the campus of UAF to explore research collaborations between the University and DOE's national laboratories.



# NATIONAL SECURITY

*"The opening of the Arctic, due to a changing climate, brings opportunity and challenge. National laboratories like Sandia can provide research and development to help the United States government and Alaska communities reduce emerging risks and ensure secure and sustainable approaches."*

*— Lori Parrott  
Sandia Atmospheric*



As an Arctic nation with significant security and national defense interests in the region, the U.S. must invest in improved Arctic capabilities. The national security community has placed increasing focus on this region and its evolving threats. Arctic-related research can inform decisions for national security missions and investments. Sandia has supported domain awareness in the Arctic for many years, including remote sensing in the Arctic, including the use of satellites, drones, tethered balloons, real-time characterization, coupled satellites and hardened buoys, and synthetic aperture radar for crevasse detection.



### SUPPORTING U.S. COAST GUARD ARCTIC SHIELD

As sea ice continues to recede, Arctic maritime activity is increasing, placing greater demands on the U.S. Coast Guard (USCG), the nation's lead federal maritime agency, for emergency response and preparedness capabilities. Safe navigation is vital, yet many parts of the Arctic Ocean are not well charted—less than 5% of the U.S. maritime Arctic has been surveyed to modern, international navigation standards.



Sandia partnered with the USCG and private industry to help the USCG build its safety case during Arctic Shield 2015. For this, a drone was launched from Oliktok Point to locate mock victims in the Chukchi and Beaufort seas. Information from the drone allowed USCG response teams to quickly and efficiently locate “victims” in the ice-covered waters of the Arctic. Two MH-60 Jayhawk helicopters from Air Station Kodiak in Alaska were deployed to a forward operating location in Deadhorse to respond to the mock incidents. Arctic Shield was instrumental in identifying some strengths and weaknesses of USCG Arctic response capabilities.

### COLLABORATING WITH THE ARCTIC DOMAIN AWARENESS CENTER

The Arctic Incident of National Significance Workshop (IoNS) series was conducted in Spring 2019 by the Arctic Domain Awareness Center (ADAC) in partnership with Sandia to discover key drivers that impact the ability of the USCG to conduct safe, secure, and effective operations. The workshops brought together public and private stakeholders to collaborate with researchers to ensure the quality and relevance of the outcomes. The outcomes will inform key research questions to direct future science and technology investments by DHS.

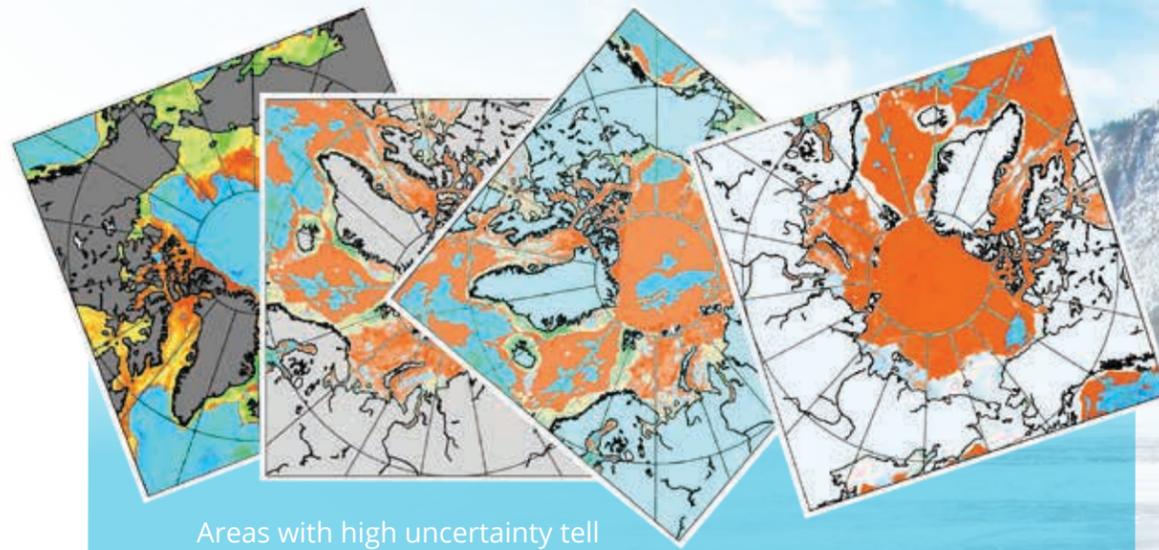
The workshops used a scenario of a major storm-driven Bering Sea maritime accident with widespread damage to coastal Western Alaska, plus an earthquake near Anchorage, to “stress the system” for shortfalls in managing a complex Arctic crisis response. The series included three workshops:

- » Alaska Native and Rural Arctic “Insights” Community Workshop; in Nome Alaska
- » Stressing the System ... Managing a Complex Arctic Crisis; in Anchorage, Alaska
- » Finding Better Meteorological Planner and Forecaster Coordination; in Anchorage.

The Insights workshop captured Native and rural perspectives to understand capabilities needed to support effective response. The objective of IoNS was to address USCG-defined areas of concern for Arctic response capability gaps related to:

- » Communications: limitations in voice and data communications;
- » Maritime Domain Awareness: understanding to effect decision-making;
- » Incident Response Logistics and Resourcing: detection of chemical or oil spills; and
- » Exercising the USCG-led Contingency Plan.





Areas with high uncertainty tell us where we need more data

#### GEOSPATIAL MACHINE LEARNING FOR FORECASTING SEA FLOOR PROPERTIES

The Arctic is a data-sparse region. Currently, less than one percent of “navigationally significant” waters in the U.S. Arctic have reliable bathymetric maps. The Naval Arctic Strategy now includes “blue water operations”, such as anti-submarine warfare, requiring accurate navigation and sonar performance. The Arctic seafloor is more prone to contain gas than non-Arctic regions, and current sonar algorithms do not consider gas in seabed sediments.

The U.S. Naval Research Laboratory developed a Global Predictive Seafloor Model (GPSM) that relies on geospatial machine learning. Sandia, the U.S. Naval Research Laboratory, and the University of Texas at Austin are collaborating to forecast Arctic marine sediment properties using the GPSM. Known data is collected and gridded, and the GPSM algorithm then looks for correlations in the data sets (e.g., porosity, heat flux, organic carbon content). Those correlations are used to predict, with a known degree of uncertainty, the values at locations where measurements do not exist. This is extremely useful in the Arctic, where it is often difficult to access areas to make direct measurements. The model produces continuous maps of seafloor properties, and uncertainty results then help guide future field measurements. These maps can help inform development of navigational infrastructure for waterways. Coupling with thermodynamic models can allow determination of geo-acoustic and geo-mechanical properties to aid in sonar performance and detection of devices of interest in Arctic waters.

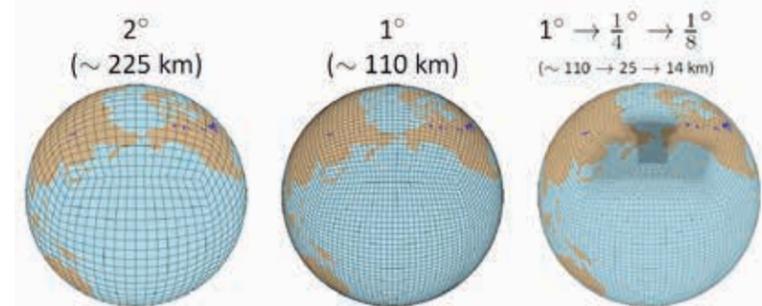




Sandia has unique capabilities to engage in research and development to address national security issues evident in the Arctic. Arctic-related research has, in turn, benefited other Sandia missions. A coordinated effort across multiple disciplines—including climate science, mathematical modeling, numerical analysis, and data acquisition—is essential in understanding Arctic systems, subsystems, and the potential impact the region has on key national security and energy security issues. A long-term commitment to collecting field observations and measurements is essential in understanding complex Arctic systems with their many feedbacks.

Sandia uses state-of-the-art, high-resolution Earth system model development and simulation tools, such as DOE's Energy Exascale Earth System Model (E3SM), to produce the best possible forecasts in the Arctic. Sandia climate researchers use high performance computing to model the complex, dynamic interactions between Earth's land surface, land ice, sea ice, oceans, and atmosphere. Sea ice has a critical influence on climate and weather patterns. Frequent, severe winter storms with strong winds can further thin Arctic sea ice. Changes in sea ice can affect deep ocean circulation. The past several decades have seen large variations in ocean circulation patterns. Understanding Earth's changing systems helps strengthen the resilience of people, the economy, energy resources, and national security.

# EARTH SYSTEMS MODELING



Sandia is helping drive advances in higher resolution Arctic and regional models that incorporate full global inputs to enable robust and efficient regional model predictions.

# POTENTIAL IMPACTS

## Permafrost thaw

Infrastructure damage

Release of gases

Potential release of ancient pathogens

## Ice sheet melt

Global sea level rise

Risk to coastal infrastructure

Ocean current disruptions

## Sea ice loss

Increased maritime activity

Increased natural resource development

Changes to mid-latitude weather and precipitation

## TIPPING POINTS

Since NASA began collecting satellite measurements in 1979, the area of the Arctic Ocean covered by sea ice has shrunk by nearly a third and has triggered a cycle in which melting ice leads to more sunlight being absorbed by the dark, open ocean. To better understand these changes and create more accurate predictions, Sandia models physical and biological changes to more accurately describe what is taking place. For example, as permafrost thaws, it releases gases such as methane and carbon dioxide. Increasing human activity also contributes to changes, as do natural events, such as gases released by volcanic activity. Sandia's models capture these feedbacks, including those between the atmosphere and ocean circulation patterns, between the ocean, sea ice, and land ice, and between sea ice floes and waves, processes that are ignored in most sea ice models.

Thawing permafrost will impact national security infrastructure such as radars, as well as natural systems, causing major alterations to Arctic regions. Continued loss of Arctic sea ice has the potential to increase regional conflicts over energy and maritime resources, decrease Arctic biological resources and fisheries, lead to habitat destruction, and impact mid-latitudes with increased severe weather and agricultural losses.



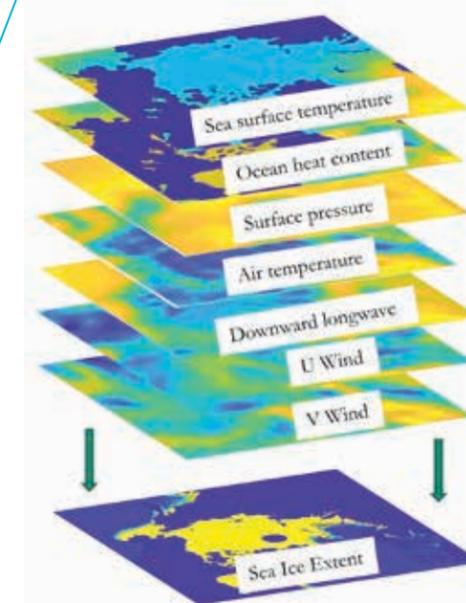
# DAKOTA

Sandia's Dakota software toolkit provides state-of-the-art, robust methods to enable the design exploration, model calibration, risk analysis, and uncertainty quantification in computational models by providing a flexible, extensible interface between the codes and a variety of iterative systems. Dakota has applications in climate modeling, computational materials, nuclear power, renewable energy, and many others.

Feedback mechanisms can have a dramatic effect on Earth systems. Understanding the behavior of specific elements, such as sea ice, in the context of a fully coupled model system, is critical for making accurate predictions. Applying uncertainty quantifications methods, such as Sandia's Dakota software toolkit, helps develop models to predict critical transitions in the Arctic. Sandia has gathered and processed 39 years of Arctic satellite sea ice data and ocean and atmosphere reanalysis data, and has begun training the data analytic model using the processed data. The data analytic model will provide insight into factors affecting sea ice.

Sandia scientists have also begun running coupled E3SM simulations and recently completed 220 years of low-resolution preindustrial control simulations to provide an estimate of the internal variability in the model. This will allow them to separate out the impacts of internal variability from external forcing agents.

Modeling high-consequence events can inform strategies for tipping event indicators and support potential mitigation efforts. Results can provide an understanding of feedback mechanisms and sea ice stability, while directly informing questions about Arctic navigability, something of critical importance to the U.S. Navy and Coast Guard, as well as private enterprise.



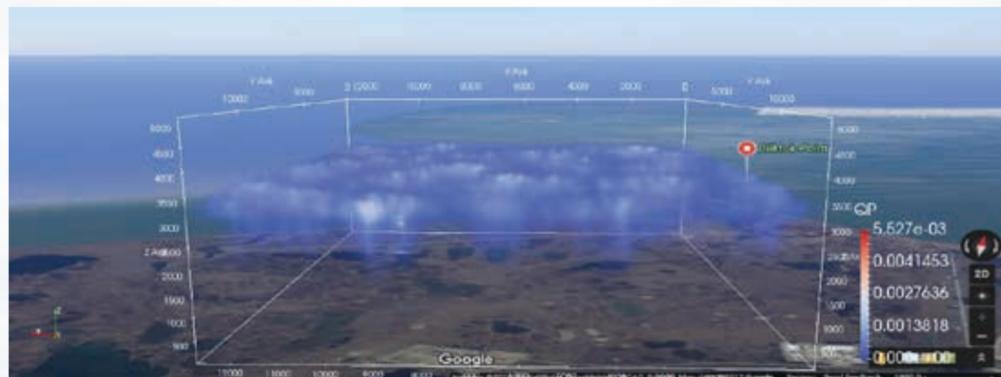
Examples of data types being used to develop predictions of sea ice variability and to evaluate potential elements to monitor for future Tipping Point cascade of events.

## UNDERSTANDING LOW-LYING CLOUDS

Atmospheric clouds play a key role in heating and cooling the planet's surface. Low-boundary layer clouds—those clouds located within the first few kilometers of the earth's atmosphere—show the greatest sensitivity to outside factors. Sandia researchers explored and compared four different model types to see if they could obtain a better representation of low-lying clouds in their models. Because robust datasets on the liquid water content in Arctic clouds are sparse, Sandia researchers also collected in situ measurements of low-lying clouds using sensors on a tethered balloon system (TBS) to constrain and compare with the models. The project is bridging the gap between atmospheric in situ measurements and model representations of these clouds.

For the first time, near-continuous large eddy simulations (LES) were performed to simulate in-cloud dynamics that occurred during the TBS measurement campaigns. This LDRD was the first step in understanding how global LES simulations might represent low-lying Arctic clouds, bridging different models with different resolutions under similar conditions to understand their ability to accurately represent these clouds. Predictions based on the atmospheric general circulation model were constrained and compared against data obtained from the more temporally- and spatially-comprehensive CALIPSO satellite space-based and ground-based radiometric measurements over North Slope Alaska. The measurements and the satellites did not compare well with the general circulation model (GCM), indicating that much more work is needed to understand actual Arctic cloud conditions.

Results showed that low-lying clouds could be better represented in GCMs by increasing the model's spatial resolution, and future work in model physics and retrieval algorithms will reduce biases in cloud-phase partitioning. The research also provided the scientific community with a valid multi-year dataset of liquid water content in low-lying Arctic clouds. Other beneficiaries of this research include groups that use weather forecasting to quantify the ice build-up on aircraft.



Sandia collected in situ cloud measurements in the atmosphere at Oliktok Point over multiple seasons. Using the restricted airspace managed by Sandia, a TBS with sensors was able to collect measurements for long periods of time without being interrupted or restricted by other air traffic.



## INVESTIGATING THE EFFECTS OF ICE-COVERED DUST PARTICLES

Mineral aerosols can behave as ice nuclei. Sandia is investigating how ice grows on mineral aerosols (essentially dust particles) to model the potential effects of ice-dust particles on clouds and weather patterns. Mineral aerosols trigger precipitation and control cloud solar reflectivity and residence time in the atmosphere. They also play a critical role in mixed-phase clouds because they allow ice to form under warmer conditions than they otherwise would.

Sandia researchers focused on potassium feldspar, considered the most effective mineral promoting ice growth overall and at higher temperatures than other major mineral dust types. Researchers seek to better understand how ice evolves on its surface. Ice was “grown” on feldspar layers under controlled lab conditions, and monitored using an optical camera. At low humidity, there are only a few dispersed ice nuclei, while at higher humidity, typical of mixed-phase clouds, the ice propagated more quickly across the feldspar surface.

Recognizing the significance of potassium feldspar as an ice nucleator, Sandia modified DOE’s E3SM atmospheric code to include two dust species: feldspar alone, which nucleates at a higher temperature, and all other mineral dust, which nucleates at a lower average temperature. This is an important step to improve the accuracy of atmospheric modeling.



# MEASUREMENTS AND MONITORING



## HELIOTROPE: USING HOT AIR BALLOONS TO MONITOR LOW-FREQUENCY SOUND WAVES

Sandia recently developed the Heliotrope, a solar hot air balloon that can loft sensors into the stratosphere, twice as high as commercial aircraft fly. This has enabled capturing low frequency sounds that are otherwise very difficult to obtain. The research community and other programs can benefit from these capabilities. Heliotropes have great potential in the Arctic where it is difficult to deploy ground-based sensors, but perpetual summer sunlight permits flight for perhaps weeks at a time.

Recognizing the need for a more complete monitoring network for infrasonic waves—sound waves below audible range—Heliotropes were tested to deploy drifting microphones. Infrasonic waves can be the result of natural events, such as volcanoes and earthquakes, as well as activities of national security interest, such as military maneuvers and defense weapons testing.

Sandia's research validated the utility of Heliotrope balloons to deploy sensors to directly observe infrasound that seldom reaches the ground, such as waves from supersonic aircraft trapped in elevated atmospheric ducts. Free-floating microphone networks have unique advantages compared to ground sensors, such as less wind interference, and the potential to pinpoint the exact location of a source that repeats itself. Sandia's Heliotrope capabilities are ideal for carrying out sensing and stratospheric monitoring during the Arctic summer.

## QUANTIFYING METHANE EMISSIONS AND IDENTIFYING THEIR SOURCE

Accurate data on methane emissions is essential for climate models, and complying with the 2015 Paris Climate Agreement, which the U.S. cannot exit before November 2020. Current approaches to measure regional emissions are fraught with problems and high uncertainty. Sandia is demonstrating an approach that relies on measurements of co-emitted gas species, like ethane, to fingerprint a methane source. This is then applied to Bayes' theorem, to provide probabilities based on known data points. The project will deliver software capable of estimating atmospheric methane quantities attributable to emission sectors, such as natural gas production, enteric fermentation (ruminant animals), landfills, wetlands, and permafrost thaw.

The approach was tested at two sites, one in the continental U.S. and one in Utqiagvik, Alaska. Methane emissions from the oil and gas sector are a key component of global emissions, but are often underestimated. Ethane can be a powerful indicator of oil and gas operations as it is co-emitted with methane and has no significant biological source.

The Greenhouse Observing Satellite (GOSAT) provides global, state-of-the-art measurements, but its precision is low compared to in situ sensors, and reconciling estimates between the two has not been successful. The inclusion of multiple gas species in the analysis is complex. Sandia uses a novel combination of measurements and models to handle the heterogeneous data required to attribute methane emissions sources across multiple sectors and large regions. Weather prediction and air quality models with Lagrangian particle dispersion models for atmospheric simulations are used.

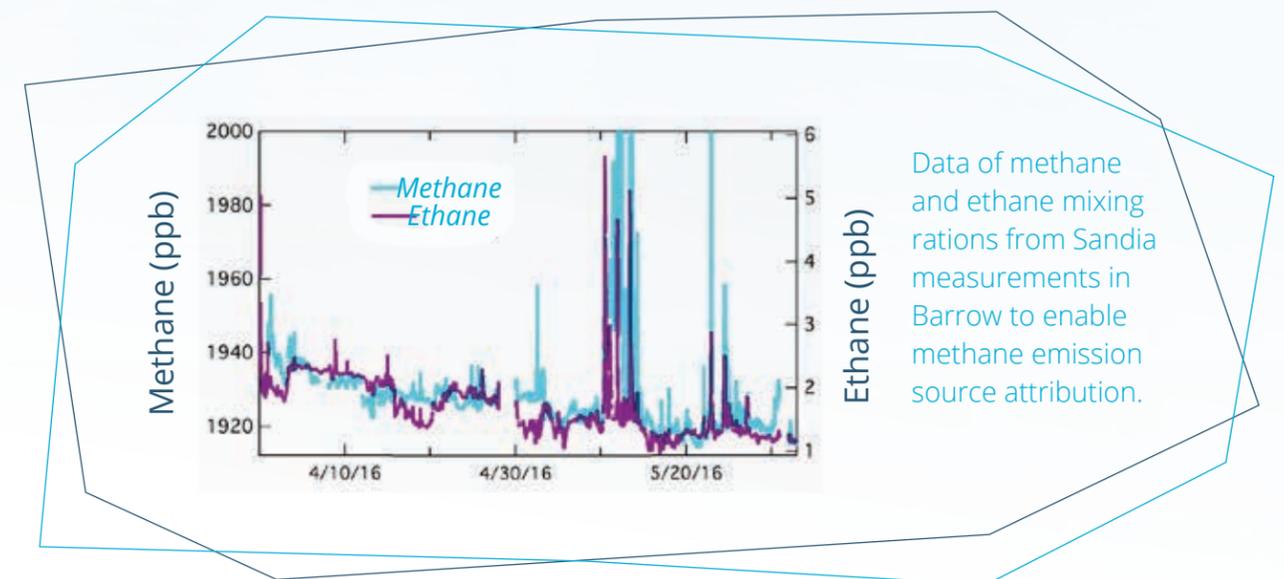
The natural gas facility in Utqiagvik presents a unique opportunity to test Sandia's method because the site is relatively isolated in a pristine background. Sandia leverages existing measurements made during its permafrost study at the ACRF to test modeling algorithms that target the natural gas sector. Traditional Gaussian assumptions are used for the modeling, followed by a probabilistic, non-Gaussian approach, using Markov Chain Monte Carlo, for Bayesian analysis.

## OPTIMIZING METHANE MONITORING NETWORKS

Methane is about thirty times more efficient at trapping solar radiation than carbon dioxide over time, so detection and mitigation of methane leaks is very important. Sandia is optimizing sensor networks to detect methane emissions from natural gas production. It is not feasible to place sensors downwind of every potential leak, so optimal placement is vital. Sandia developed Chama, a software package using mixed-integer linear programming, to optimize the type and placement of sensors. Chama enables the design of sensor networks that minimize impact (e.g., time to detection, plume extent, population impacted) or maximize coverage. Sensor network optimization requires a set of simulations that model site-specific scenarios, capturing uncertainties in wind and emission characteristics. Chama can be used for a wide range of applications, such as deployment of other field sensors to improve national security.

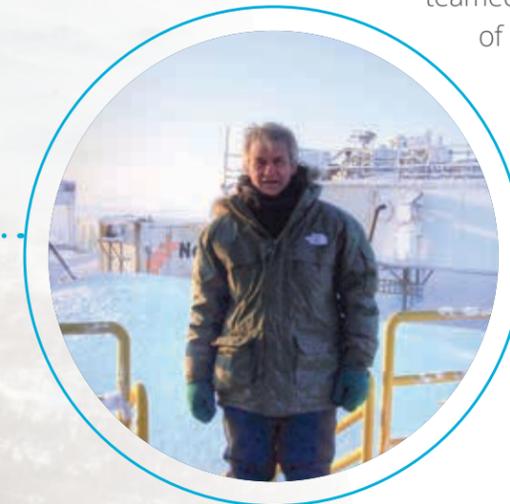
## LONGEST CONTINUOUS SET OF METHANE MEASUREMENTS AT NORTH SLOPE ALASKA

Over nearly a three-year period, between 2014 and 2017, Sandia collected a continuous set of measurements at North Slope Alaska (NSA) for methane, methane isotopologues, ethane, carbonyl sulfide, and black carbon. Additional measurements were collected for carbon monoxide, carbonyl sulfide, carbon dioxide, and water vapor. Instruments were deployed at the National Oceanic and Atmospheric Administration (NOAA) Barrow Observatory and the DOE ARM sites. High-resolution measurements of black carbon were collected using a single-particle soot photometer. These measurements are important to refine models of atmospheric processing of black carbon and allow detailed comparisons between high-resolution atmospheric transport models and long-term measurements. Preliminary analyses of the data show some interesting trends, including seasonal variations in methane emissions. The measurements also indicate where the largest sources of methane are in Utqiagvik, Alaska.



# CONCEPT FOR A HIGH ARCTIC RESEARCH CENTER

Science and research are critical to inform national policy and responses to rapid Arctic change. Conducting this science requires a world-class Arctic research facility with year-round access. That is why Sandia and UAF have teamed up to advance the concept of a permanent, comprehensive multi-agency U.S. High Arctic Research Center (USHARC) in the Prudhoe Bay area. Sandia and UAF are actively engaging federal agencies, academic institutions, non-governmental organizations, and international partners to support its development.



*For the last 40 to 50 years, the Arctic environment has been changing at twice the rate of what's happening globally, and during the last 20 years, it has accelerated to nearly three times the global pace."*

— Jasper Hardesty  
Sandia Earth Sciences  
Researcher

The USHARC is envisioned as a national asset supporting a comprehensive Arctic science and security network that addresses the needs of multiple stakeholders, including government, industry, Arctic communities, and academic researchers. The facility would fill critical mission gaps while addressing economic development, environmental protection, and national security needs. It would provide direct access to the Alaska High Arctic and facilitate work on all areas of research, technology development, natural resource use, energy systems and infrastructure, use of autonomous systems, domain awareness and remote sensing, and improved understanding of Arctic processes to improve models and forecasts.

The proposed location for the USHARC is the Prudhoe Bay area, about 450 kilometers above the Arctic Circle. The concept is to connect and integrate a network of U.S. Arctic research facilities, including the Toolik Field Station, the Barrow Arctic Research Center/Environmental Observatory, the National Science Foundation Arctic Lagoons Long-Term Ecological Research site, and the NOAA Barrow Observatory. The long-range vision is to create a 'string of pearls' to develop a coordinated North American Arctic research infrastructure.

The proposed USHARC location would provide direct access to the Arctic Ocean as well as coastal and terrestrial areas and is the only Alaska High Arctic location accessible by road to sub-Arctic Alaska and the lower 48 states. There is regular commercial air service, and Oliktok Point is also the only location in the U.S. High Arctic with controlled airspaces, which Sandia manages for the DOE. Special Use Airspace includes a 74-km wide by 1,246-km long area from Oliktok Point toward the North Pole. USHARC could represent an important staging area for search and rescue operations in coordination with lead agencies, as demonstrated during the U.S. Coast Guard 2015 Arctic Shield exercise—described in this report's National Security section.

Through relationships with NSA partners, such as oil and gas companies and Alaska Native Corporations, the USHARC could provide equipment, skills, and services. Resources and infrastructure that serve industry include medical facilities, skilled maintenance, and utilities, such as high-speed fiber-optic data lines. The USHARC facilities would be made available to all stakeholders to conduct collaborative research such as:

- » Unmanned aircraft systems (UAS) test facility with a dedicated airstrip and hangar;
- » Laboratories for research, testing, and technology development;
- » Offices, lodging, and core support facilities;
- » Networked meeting spaces for teaching, training, and workshops;
- » Research preparations, shipping, storage and maintenance facilities, and
- » Field equipment with logistic and operational support.

USHARC can enable Arctic technology development through collaborative partnerships, such as the "ZERO/V", where Sandia partnered with the Scripps Institution of Oceanography, Glosten naval architects, and the classification society DNV GL to assess the design and feasibility of a hydrogen fuel-cell coastal research vessel.



# CONCEPTUAL DESIGN

Conceptual designs and cost estimates have been completed for the USHARC as a multiphase project.

## PHASE 1

Master Plan: construct roads, pads, infrastructure. A preliminary Environmental Assessment was conducted, and no evidence of contamination was found at the Oliktok Point site.

## PHASE 2

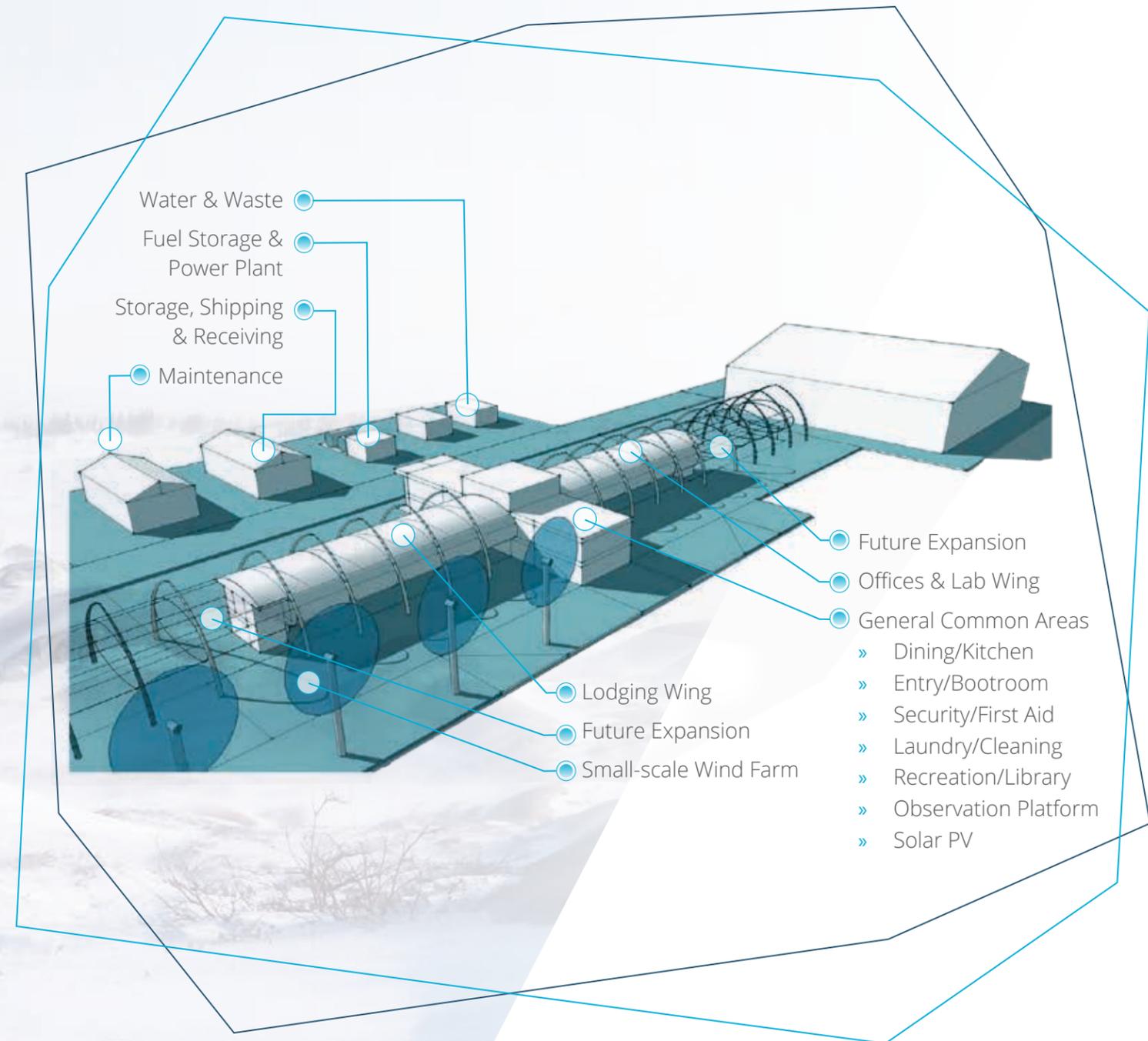
Core facility for basic year-round campaign capability of small-scale operations: Commons core, Lodging, Lab, UAS Center, Maintenance & Support Center: Approx. 4,700 sq. meters total.

## PHASE 3

Update Master Plan: expand facility scale, systems, and capabilities. Marine dock and support facilities, marine vessels, portable lab trailer, portable shelter(s): Approx. 1,300 sq. meters added building area, new pads.

## FUTURE PHASES

Dictated by needs and priorities as established in subsequent evaluations and revised Master Plans.



USHARC DEMONSTRATION PROJECTS

During the High Arctic Boat Operations (HARBO), Sandia researchers used a marine research vessel docked out of Prudhoe Bay to deploy a temperature profile system to learn how optical fiber could be used to measure water surface temperatures. The capability will be instrumental for bridging knowledge gaps in Arctic cryospheric processes. Researchers also installed a ground station for tethered balloon system (TBS) flights, tested an auto-reeler system for small payload TBS, and performed ocean depth measurements near the Oliktok Point shore to inform future exercises and USHARC planning.



During the Gulf Boat Operations demonstration, two Sandia departments (Atmospheric Sciences/8863 and Microsensors/8634) coordinated to test sensors in the marine environment to detect hydrocarbons and other compounds, key for monitoring the impacts of oil and gas operations in the Arctic. Large TBS platforms were flown from a marine vessel, and continuous ocean-atmosphere vertical temperature profiles were obtained to develop capabilities with important applications to science questions in the Arctic.



# TETHERED BALLOON SYSTEM

## INSTRUMENTS & MEASUREMENTS

### Aerosols

Printed optical particle spectrometer for aerosol concentrations and size distributions

Miniature scanning aerosol solar photometer for aerosol optical depth profiles

Condensation particle counter for aerosol size distribution

### Meteorology and Thermodynamics

Tethersondes measure pressure, relative humidity, temperature, wind speed/direction, altitude, latitude/longitude

Distributed temperature system for temperature profiles

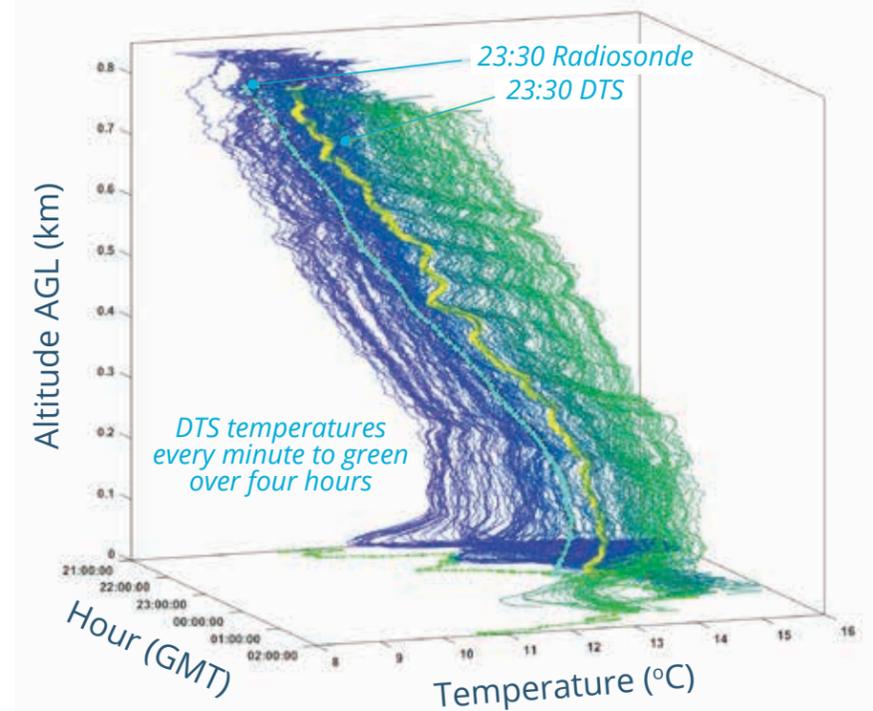
### Ice and Liquid in Clouds:

Supercooled liquid water content sensors for cloud liquid water content

Video ice particle sampler for ice microphysics observations



TBS DTS Temperature Profiles  
1-minute DTS temperatures every 1m from the surface to the balloon



## USHARC DEMONSTRATION PROJECTS

The Joint UAS-Balloon Activities (JUBA) was a collaborative demonstration between Sandia departments 8863/Atmospheric Sciences and 6533/Robotics R&D, to concurrently fly an octocopter and a TBS in controlled airspace at Oliktok Point. Temperature profiling systems were operated concurrently from both platforms. JUBA and portions of HARBO were conducted from the "Jump-Start Station", a temporary site to demonstrate how unmanned systems and airspace could be coordinated outside of the existing DOE ARM site.



# ARCTIC INFRASTRUCTURE

*"Sandia National Laboratories has been working in the Alaska Arctic for more than 20 years because the rapidly changing Arctic is at the forefront of a number of national security issues that include domain awareness, energy systems and infrastructure resilience. Alaska offers a unique environment for researching basic science and engineering to address security, energy, and infrastructure challenges. We are proud to partner with the University of Alaska Fairbanks and others on this important work."*

*— Dori Ellis  
Deputy Laboratories Director*

The Arctic is changing rapidly, bringing new challenges to remote communities, industry, military bases, and associated infrastructure. North Slope Alaska is very limited with respect to assets, and many unique challenges exist including permafrost.

*"Like the opening of the Atlantic and Pacific oceans in history, ramifications from a newly accessible Arctic demand national security preparedness. The timing, location, and nature of potential security risks are dependent upon combined in situ capabilities, technological advances, economic incentives, political motivations, and environmental changes."*

—Diana Bull,  
Sandia Arctic Researcher and  
Strategic Analyst Sciences Manager

There is a dire need for well-designed energy and infrastructure to support current and future needs. Wastewater treatment facilities are often the largest year-round energy users in Arctic communities. Clean water, wastewater, and energy and infrastructure are essential for developing sustainable communities. Attention to permafrost thaw when designing infrastructure, and a need for robust, mobile energy systems for extreme frigid conditions are critical. Cogeneration technologies that combine heat and electricity generation are ideal in such circumstances.

Population and infrastructure in the Arctic tend to be located near the coast due to a lack of all-season roads. Traditional piers are usually not feasible on the

Alaska coast due to ice floes, and special considerations for coastal dynamics, silting, and erosion must be made. Rapidly warming conditions in the Arctic thaw permafrost, making the ground unstable, causing sea levels and wave heights to rise, accelerating the erosion of coasts and riverbanks, which pose a special risk to infrastructure. Not only are homes and buildings threatened, but roads become unstable, limiting land-based travel.



The impact on infrastructure is further exacerbated by increased exploration and exploitation of natural resources, and increased tourism, placing greater demands on existing infrastructure and creating demands for new infrastructure. A deep-water port in Alaska is essential, but Arctic infrastructure development costs are three to five times that of less remote locations.

In response to these challenges, Sandia funded projects to help predict physical changes of coastlines and risks to Arctic infrastructure, focusing on renewable energy systems, and optimizing infrastructure planning.

## PREPARED

The Partnership for Responsible Planning for Arctic Resilience and Development (PREPARED) is a collaboration between UAF and Sandia to increase resilience through modeling and analysis across infrastructure and natural systems in Alaska and the Arctic.

The collaboration will:

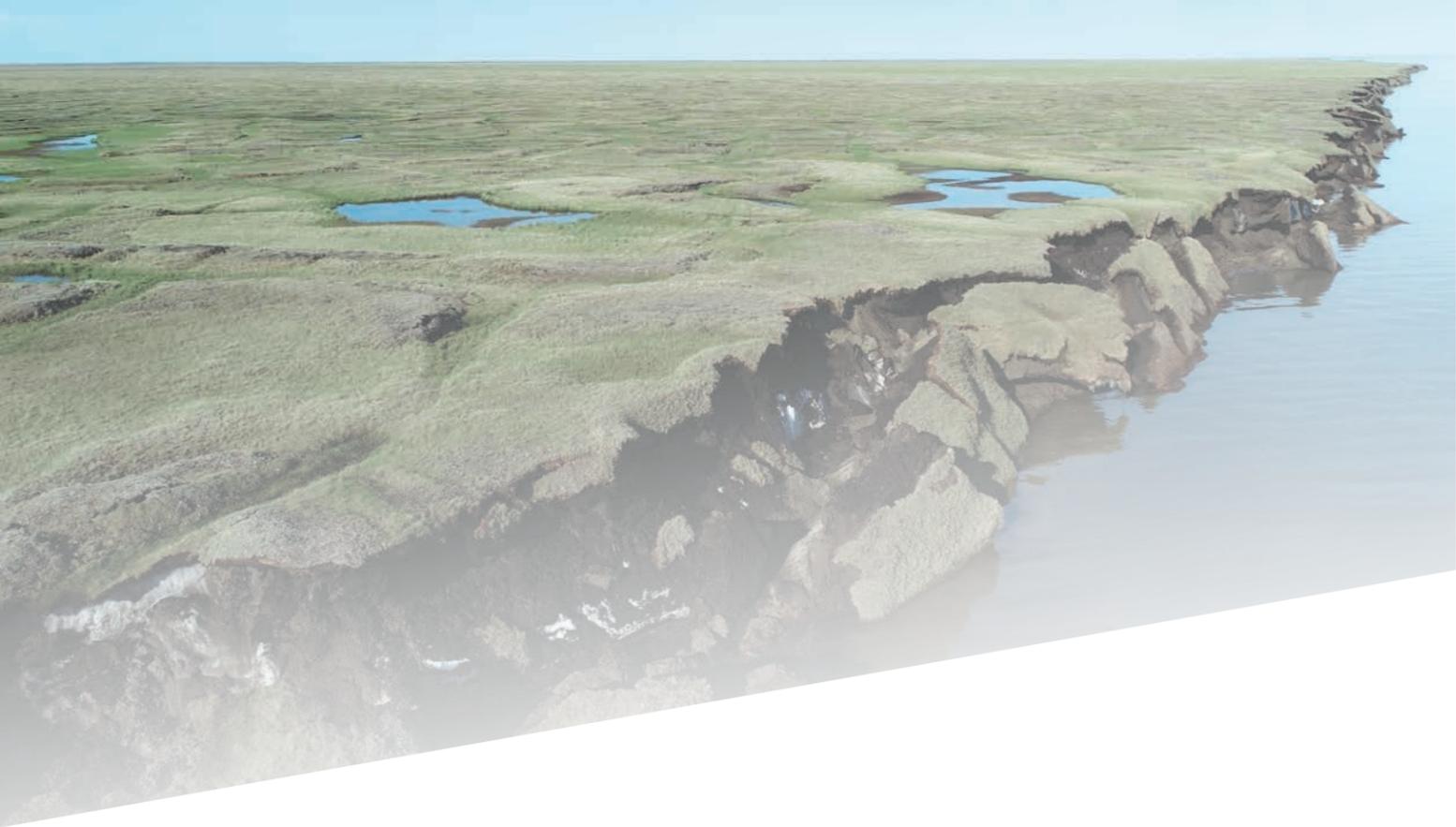
**Improve** emergency planning and preparedness and enhance response to emergencies and disasters, whether natural or human-induced

**Improve** knowledge of the risks and adaptations necessary to increase the resilience of the natural, engineered, and social systems

**Support** long-term planning for adaptation to changing climate and environmental conditions, new activities and land uses, and community transitions

**Strengthen** the nation's infrastructure and analysis capabilities by providing novel test conditions and expansion of infrastructure models.





## PREDICTING ARCTIC COASTAL EROSION

The U.S. has over 10,000 km of Arctic coastline, including more than 1,600 km bordering the Arctic Ocean above the Arctic Circle. Coastal erosion rates in the region are accelerating at an unprecedented rate due to thawing permafrost and melting sea ice. Unlike other coastal areas, sediments of the Alaska coastline are held together by ice within permafrost, so the coastline is susceptible to erosion as permafrost thaws. The reduction in sea ice accelerates this process by allowing larger ocean waves to strike the shore. These waves thaw the permafrost and undermine large blocks of coastline that dislodge and fall into the sea. Portions of the northern Alaskan coastline near Drew Point are eroding at a rate of up to 20 meters per year, and some areas are eroding even faster.

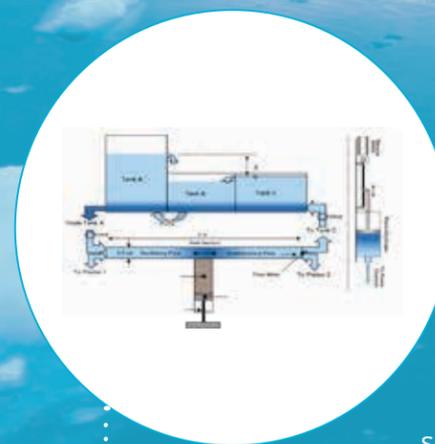
Arctic ecosystems are releasing large fluxes of organic matter, such as carbon and nitrogen, previously stored in permafrost. The Department of Defense is struggling to fortify coastal radar sites operated to ensure national security and detect missiles. The receding coast also impacts shoreline fuel storage systems, and contaminated defense sites. This is having a profound impact on Arctic communities who depend on sea life for their primary food supply, and fuel for heat. Lacking a consistent national presence or adequate infrastructure, these communities are the eyes and ears that monitor growing international activity in the U.S. Arctic.

Recognizing the need for better coastal erosion models, Sandia is participating in a collaborative effort with researchers from the U.S. Geological Survey, the University of Alaska Fairbanks, the University of Texas at Austin, and Integral Consulting to develop new models that:

- » Inform risk management decisions on critical infrastructure, such as the fortification or relocation of coastal radar sites, airstrips, roads, and communities,
- » Estimate and track sediment and organic fluxes into the Arctic Ocean, and
- » Identify driving variables in the permafrost erosion process.

Current models are based on mechanical sediment transport processes seen at non-Arctic coastal regions rather than the thermo-chemical-mechanical processes at work in the Arctic. Sandia's process-based Albany model couples environmental conditions causing erosion with a multi-physics representation of the coastline to capture the thermal-chemical-mechanical interdependencies prevalent in Arctic coastal erosion.

The results from this Sandia-funded research will guide military and civil infrastructure investments and increase understanding of how the eroding coastline will affect nearshore ecological stability.



## SEAWOLF

Sandia developed the Sediment Erosion Actuated by Wave Oscillation and Linear Flow (SEAWOLF), an apparatus that utilizes in situ core samples and provides direct measurement of erosion rates from combined wave-current action. Erosion rate measurements by the SEAWOLF enable development of a constrained, coupled hydrodynamic wave and coastal erosion model. The SEAWOLF data uniquely provides erosion rates as a function of depth below the sediment-water interface and the time varying shear stress at the bottom of the ocean in wave dominated environments. No other device can obtain wave generated sediment erosion measurements to parameterize model inputs. These measurement and modeling techniques have been employed and proven at several coastal and harbor locations in the U.S., including West Alaska for the Army Corps of Engineers.



# RENEWABLE ENERGY

## AND GRID TECHNOLOGIES

*"Access to affordable and resilient electricity is a challenge for many Alaska communities, and that harsh environment provides a really useful proving ground for new energy technologies, such as advanced power electronics and resilient systems, that will eventually have to be applied to the rest of the grid."*

*—Abe Ellis  
Manager for Renewables  
and Distributed  
Systems Integration*

Alaska is home to several military installations, so a reliable and resilient power supply is important not only to the survival of civilians, but also for national security. Arctic energy production, storage, and delivery of the future should be:

- » Flexible and distributed, providing energy for a wide variety of load and resource scenarios
- » Mobile, capable of being moved from place-to-place as needed
- » Self-contained, able to operate without long, expensive supply chains
- » Scalable to allow power systems to grow as load demand grows
- » Robust to both immediate and long-term events.

Sandia collaborates with other national laboratories, local utilities, academic institutions and industry to understand how renewable energy systems and grid-integration technologies perform in the Arctic where harsh weather and rugged conditions, as well as natural and man-made disasters, can all affect the power supply.

A microgrid is a small-scale electrical grid that can connect and disconnect from the main grid as needed to provide a more reliable and continuous source of power to communities susceptible to power outages. Alaska is home to more than 200 microgrids, representing over half of all microgrids in the U.S. Alaska's remote microgrids usually do not connect to a main grid due to their geographical isolation.

## RADIANCE MICROGRID PROJECT

The Radiance project—Resilient Alaskan Distribution System Improvements using Automation, Network Analysis, Control, and Energy Storage—is a three-year, \$6.2M project that deploys advanced technologies and methods to enhance the resiliency of the electrical grid in Cordova, where harsh weather conditions, high energy costs, and changing grid conditions threaten the city's energy supply. Sandia plays a key role in the project, led by Idaho National Laboratory, and includes team members from the City of Cordova, Cordova Electric Cooperative (CEC), Alaska Village Electric Cooperative (AVEC), and UAF's Alaska Center for Energy and Power (ACEP).

Sandia is responsible for designing Cordova's microgrid operations technologies, such as the inverter controls, protection systems, and protection relays. Researchers and analysts use the Microgrid Design Toolkit (MDT), a software tool developed by Sandia and funded by the DOE, to evaluate alternative microgrid designs based on performance, reliability, cost, and other factors. The design and operation of the cyber-resilient microgrid is then field-tested through linked testbeds at DOE labs using a digital real-time simulation of the existing Cordova microgrid. Sandia then refines the design using the MDT prior to implementation.

Approximately 2,600 people in Cordova, Alaska, rely on a microgrid, served primarily by two hydroelectric plants and a diesel power plant. During the winter, Cordova's population is dependent on high-cost diesel to meet their energy needs.

SANDIA  
IS WORKING  
— TO MAKE —  
MICROGRIDS...

Safe

Reliable

Resilient

Sustainable

Affordable

Scalable

# SWEPT

The Sandia Wave Energy Power Take-Off (SWEPT) is a mobile lab, housed in shipping containers. The SWEPT lab, specifically designed for systems generating electricity from ocean waves, simulates ocean waves in a controlled environment. Hydraulic systems in SWEPT mimic how wave behaviors affect wave energy converters that produce energy from ocean waves, along with the generator and power takeoff systems of wave energy converters.

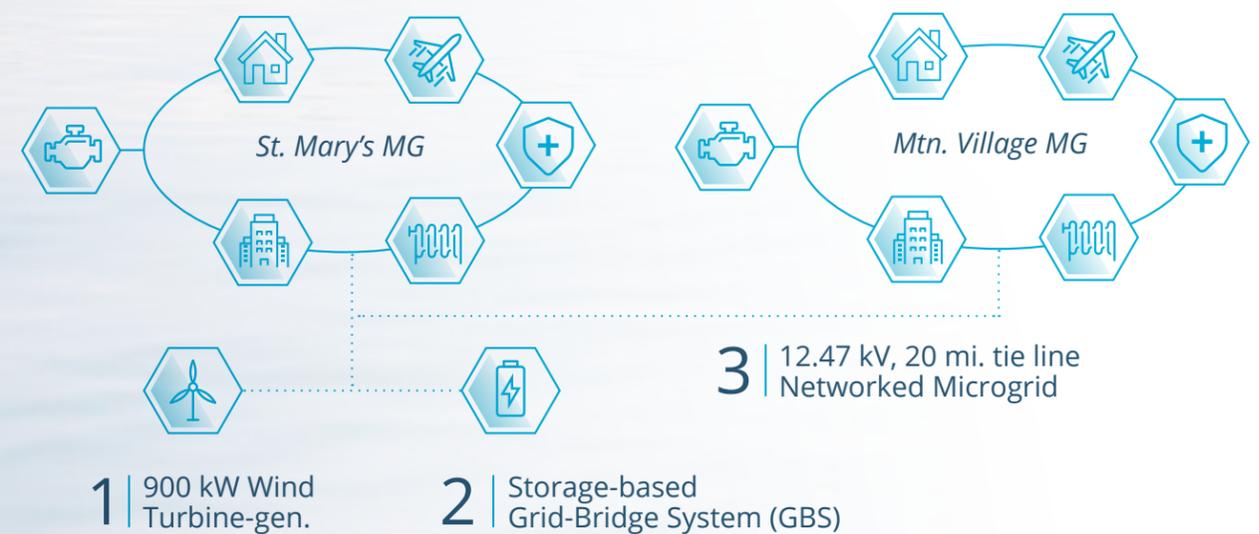
## OCEAN WAVE ENERGY FORECASTS

Sandia is partnering with UAF-ACEP to improve the performance and reliability of ocean wave energy (marine hydrokinetic) technologies. Wave power devices extract energy directly from surface ocean waves or from pressure fluctuations below the ocean surface. Sandia and UAF-ACEP are improving the accuracy of wave forecasts to facilitate integration of marine hydrokinetic technologies into the microgrid at Yakutat, Alaska. The community is 100 percent reliant on diesel generators, which is expensive and susceptible to supply shortages, whereas wave energy is abundant. Ocean wave forecasts can be improved by applying real-time data assimilation to reduce errors in forecasts compared to existing models. Special buoys are being deployed offshore of Yakutat, Alaska, to collect wave measurements that will be used to implement data assimilation, improving the accuracy of these forecasts.

## DOE/DOD GRID BRIDGING SYSTEM

Sandia is partnering with AVEC and the UAF-ACEP to develop a storage-based, grid-bridging system that will allow remote hybrid microgrids to utilize their renewable components more efficiently and for longer periods, reducing their reliance on expensive diesel fuel. The goal is to use only renewables plus energy storage to fully meet energy demands, to dispense with diesel generators entirely. The project is developing and demonstrating advanced controls and power electronics technologies to improve the resilience of hybrid microgrids. Dynamic microgrid modeling and data collection improves the understanding of networked microgrids under a variety of conditions. The project has the potential to accelerate the development and widespread adoption of advanced grid technologies for remote communities in Alaska and the entire U.S.

### St. Mary's and Mountain Village, Alaska



## CAPTURING SOLAR ENERGY ON TWO SIDES

Sandia and UAF collaborated to study the use of bifacial (double-sided) solar photovoltaics (PV) in Fairbanks, Alaska. Although Alaska's solar resource is between one-third and one-half that of the lower 48 states, it is economical and can be made more so using bifacial PV. Bifacial PV panels have significant advantages over monofacial (single-sided) panels, especially in high latitudes, because they can capture sunlight on two sides—front and back. Preliminary analyses show that bifacial PV can produce 15-30 percent more energy than monofacial PV of similar rating and cost. The key to bifacial PV's success is understanding different panel orientations and configurations to optimize performance.

A bifacial PV panel can capture substantial light scattered from clouds and surrounding surfaces, such as highly reflective snow-covered ground in the Arctic. PV generally performs more efficiently in cold temperatures. The advantages of using bifacial panels increases with increased latitude (due to lower sun angles) and increased duration of snow-covered ground. While snow can potentially block sunlight from PV panels, bifacial panels configured vertically shed snow and collect less dirt than horizontal panels. Vertical bifacial PV takes advantage of the large range of solar azimuth in the Arctic (i.e., sun rises and sets in NNE and NNW in summer) so the sun spends a lot of time at high incidence angles relative to bifacial PV faces. Sandia-UAF are working to optimize the field layout to reduce shading and maximize sunlight reaching the panels.





# CONCLUSIONS

Sandia continues to be a focal point for Arctic-related science and research and to engage its research partners, state and federal agencies, and others to identify future opportunities in the region. Alaska is becoming an incubator for the development of innovative technologies that will benefit remote locations, and the entire nation. Just as the space race brought advanced technologies back to the people on Earth, development in the Arctic will bring improved technologies to the rest of world. Global ramifications are a certainty. Some future impacts of Arctic change can be modeled and predicted, while other impacts are unknown and evolving. Sandia stands ready to provide its experience and capabilities to meet future challenges and national security needs in the Arctic.

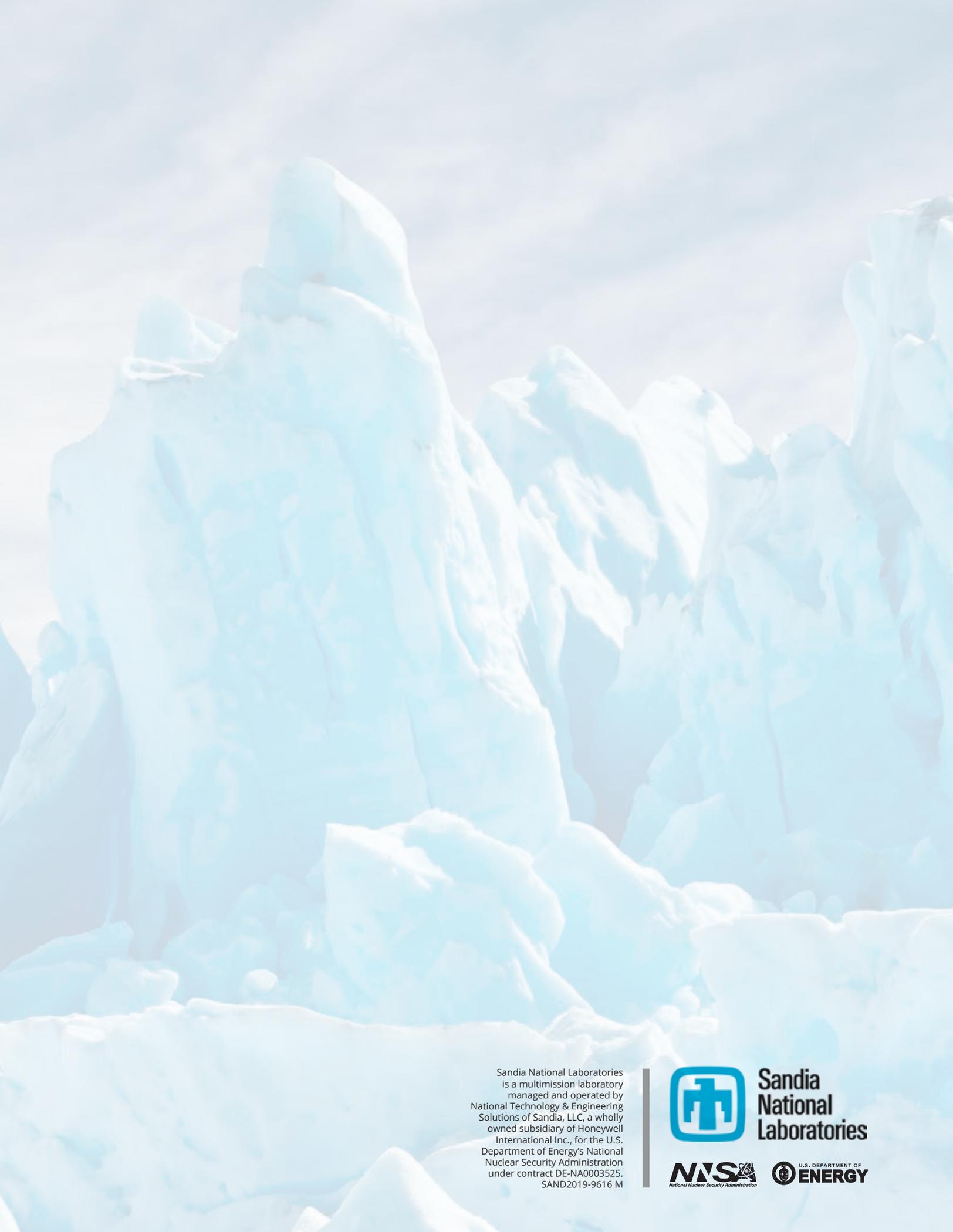
# ACRONYMS AND ABBREVIATIONS

ACEP	Alaska Center for Energy and Power
ACRF	ARM Climate Research Facility
ADAC	Arctic Domain Awareness Center (a DHS Center of Excellence)
AMF-3	ARM Mobile Facility #3
ARM	DOE Atmospheric Radiation Measurement
AVEC	Alaska Village Electric Cooperative
CEC	Cordova Electric Cooperative
CRADA	Cooperative Research and Development Agreement
DHS	Department of Homeland Security
DoD	US Department of Defense
DOE	US Department of Energy
E3SM	DOE Energy Exascale Earth System Model
GCM	Global Climate Model
HARBO	High Arctic Research Boat Operations
JUBA	Joint UAS-Balloon Activities
LDRD	laboratory-directed research and development
LES	Large eddy simulation
MDT	Microgrid Design Toolkit
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
NSF	National Science Foundation
PREPARED	Partnership for Responsible Planning for Arctic Resilience and Development
PV	photovoltaics
RADIANCE	Resilient Alaskan Distribution System Improvements using Automation, Network Analysis, Control, and Energy Storage
SEAWOLF	Sediment Erosion Actuated by Wave Oscillation and Linear Flow
SWEPT	Sandia Wave Energy Power Take-Off
TBS	tethered balloon system
UAF	University of Alaska – Fairbanks
UAS	unmanned aircraft systems
USHARC	U.S. High Arctic Research Center

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